Electroactive polymers (EAP) as Emerging Technology for Devices and Robotics

Review, Capabilities, Applications and Potential

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Outline

- Background
- What are the alternative
- Robotics and EAP
- Longitudinal and bending EAP
- Current planetary applications
- Emerging technologies to support the EAP infrastructure
- Future development and applications

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What is an Electroactive Polymer (EAP)

- EAP materials are polymers that exhibit change in a property or a material/physical characteristic as a result of an electrical stimulation (field, current, etc.).

- Changes can involve physical deformation, optical or magnetic variation and others.

- The emphasis of this course is on EAP materials that display electro-mechanical reaction.
  - The majority of the course material will focus on actuation capabilities.
  - Sensing will be discussed mostly in relation to IPMC materials.

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Background

- Electroactive polymers (EAP) are emerging with behavior that mimic biological muscles.
- These materials can be used to produce actuators that are miniature, light, inexpensive, miser and best of all large displacement inducers.
- Tests have shown that certain EAP materials operate effectively also at cryogenic temperatures and vacuum.
- The technology enables unique actuation to support various mechanisms, robotics and locomotion needs.

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Comparison between EAP and widely used transducing actuators

Property	EAP	EAC	SMA
Actuation strain	>10%	0.1 - 0.3 %	<8% short fatigue life
Force (MPa)	0.1 – 3	30-40	about 700
Reaction speed	μsec to sec	μsec to sec	sec to min
Density	1- 2.5 g/cc	6-8 g/cc	5 - 6 g/cc
Drive voltage	1-7V/ 10-100V/μm	50 - 800 V	NA
Consumed Power*	m-watts	watts	watts
Fracture toughness	resilient, elastic	fragile	elastic

* Note: Power values are compared for documented devices driven by such actuators.

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Historical perspective

- The pioneering of the EAP field can be attributed to Eguchi's 1925 reported discovery of an electret material*.
  - Obtained when carnauba wax, rosin and beeswax are solidified by cooling while subjected to DC bias field.
- Another important milestone is the 1969 observation of a substantial piezoelectric activity in PVF2.
  - PVF2 films were applied as sensors, miniature actuators and speakers.
- Since the early 70's the list of new EAP materials has grown considerably, and the most progress was made in this decade.
  - This EAPAD conference of SPIE, initiated by its Chair, is the first conference on this subject.
- Even though many EAP were already introduced, the number of commercially used ones was mostly limited to PVF2/TRFE materials and ceramic/ polymer composites.

* Electrets are dielectric materials that can store charges for long times and produce field variation in reaction to pressure.

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The evolution of EAP

- The large-displacement actuation combined with other attractive characteristics (light, resilient, consume low-power, long fatigue life, low cost and rapid respond) offer incentives to pursue their application.

- Some of the leading emerging EAP materials are:
  - Electro-Statically Stricted Polymers (ESSP) exhibiting several tens of percents actuation strain.
  - Ionic-gel demonstrating over 50% contraction.
  - Ion-exchange Polymer membrane Metal Composites (IPMC) bending to closed loop.

- Even though some of these materials offer actuation displacement capabilities that are similar or exceed the performance of biological muscles, their force actuation is relatively small.

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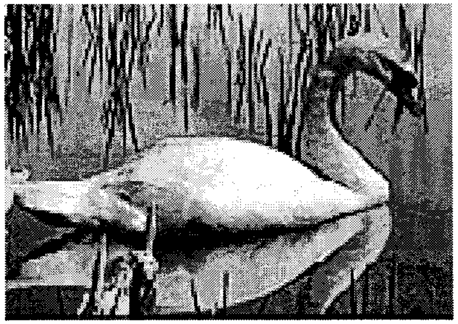
BIOLOGICALLY INSPIRED ROBOTICS

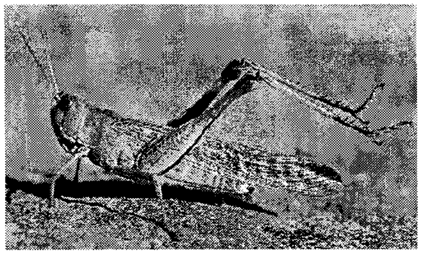
MULTI-TASKING IN-SITU MISSIONS USING SCALABLE AUTONOMOUS ROBOTS FOR COLONIZED PLANETARY EXPLORATION

Multiple locomotion capabilities

Flying, walking, swimming & diving



Hopping, flying, crawling & digging



Coordinated robotics

Examples from nature offer ideas for scalable autonomous robots that can be used to colonize planets and perform multi-tasking in-situ exploration missions

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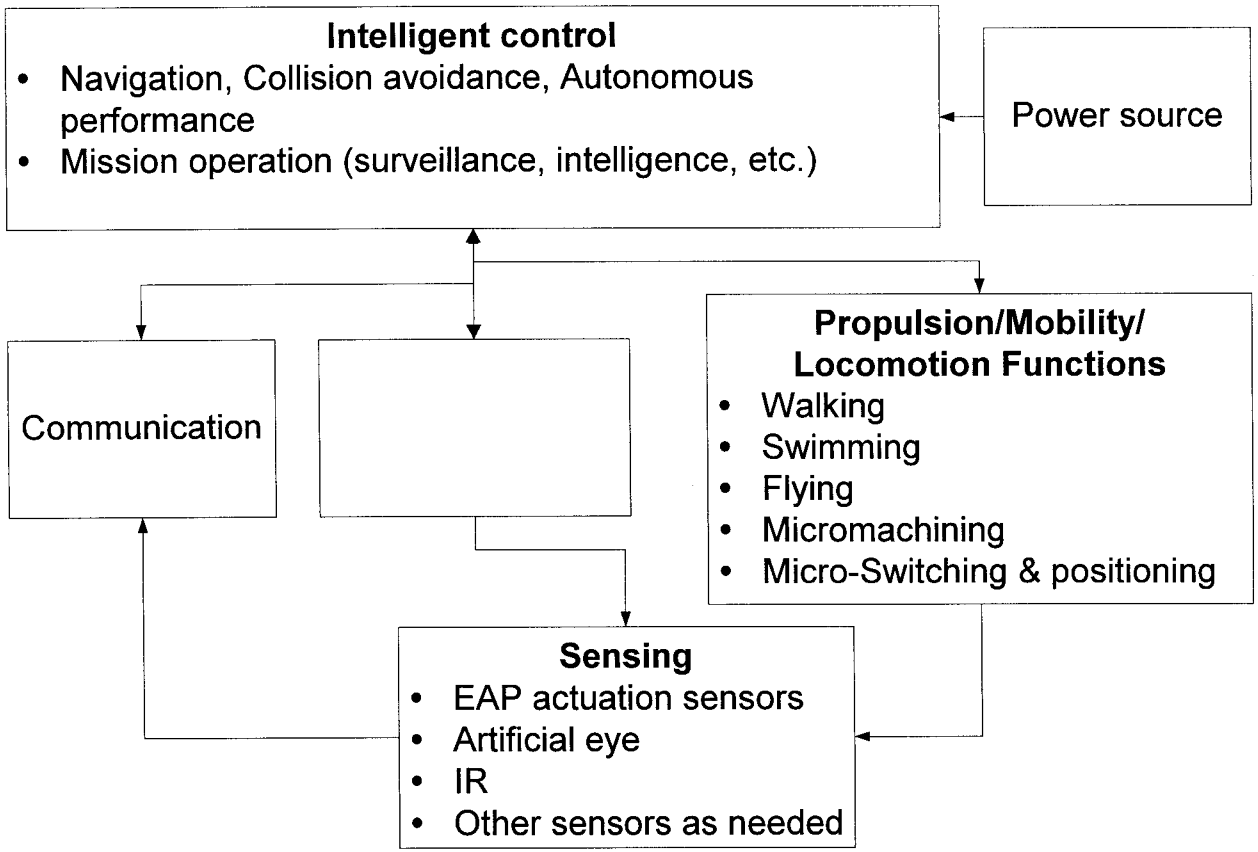
Potential EAP applications for robotics

- EAPs offers unique characteristics to produce highly maneuverable, noiseless, agile biomimetic miniature robots.
- EAP actuators can be used to produce mechanisms with simple drive signals but the nonlinear behavior needs to be taken into account.
- Such materials can be used to provide the necessary locomotion drive mechanism of insect-like (flying, crawling, swimming, etc.) robots at sizes that range from microns to several centimeters.
- The development and application of EAP materials and mechanisms involves interdisciplinary expertise in chemistry, materials science, electronics, mechanisms, computer science and others.

Elements of an EAP actuated system



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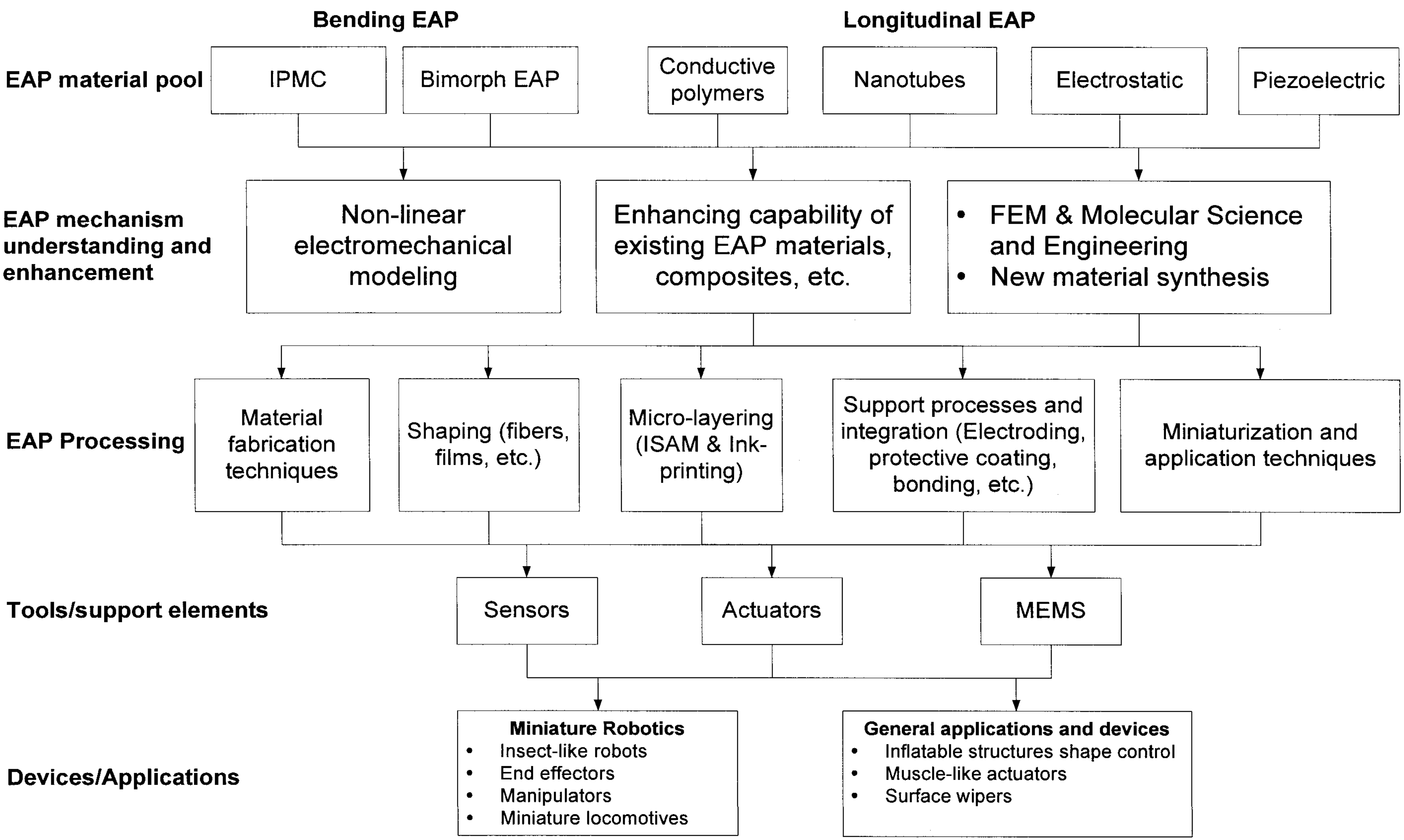
EAP infrastructure



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Technology status

- Bending and longitudinal EAP actuators are developed by numerous research institutes, academia and industry.
- Various unique capabilities and applications are investigated.
- EAP changed the paradigm about robotics construction - polymer materials can serve simultaneously as a structural element, actuator and end-effector.
  - Conventional robots are driven by mechanisms that consist of motors, gears, bearings, etc.
  - Electroactive polymers (EAP) offer alternative simple and direct actuation with resilience and toughness emulating biological muscles.
- The potential for space, medical, commercial, military and other applications are great but the main limiting factor is their low force actuation capability.

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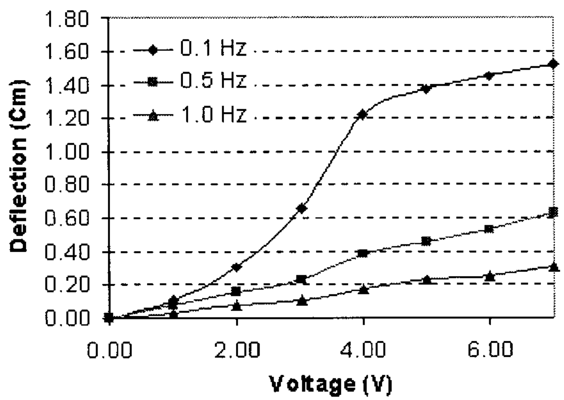
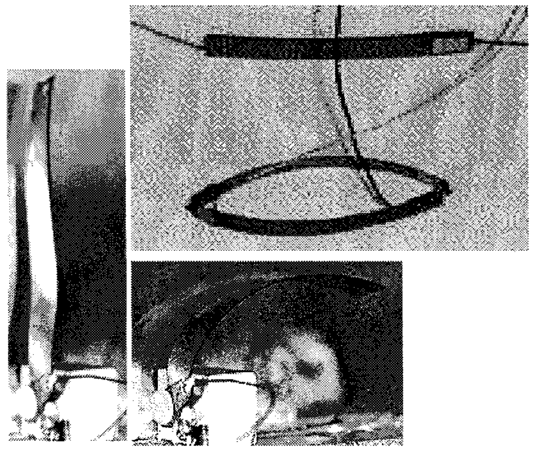
Bending and longitudinal EAP

examples





Ion-exchange Polymer membrane Metallic Composite (IPMC) can bend by over 90° under ~3-4V and ~30-50-mW.

31-mm wide, 50-μm thick Electrostatically stricted polymer (ESSP) film extending over 12%

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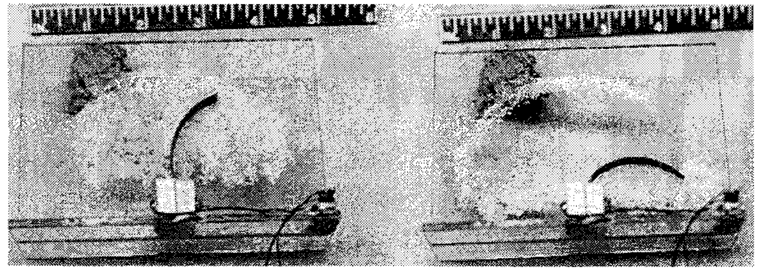
EAP mechanisms developed at JPL

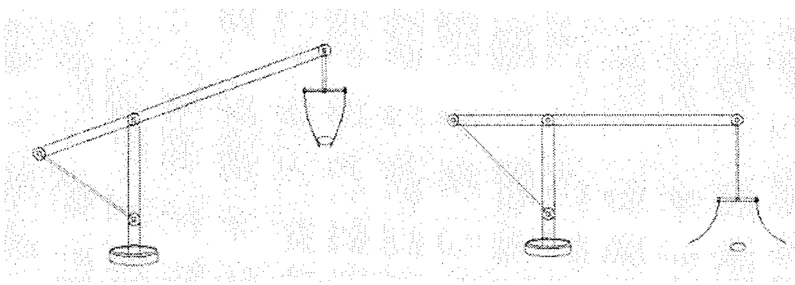
Dust wiper

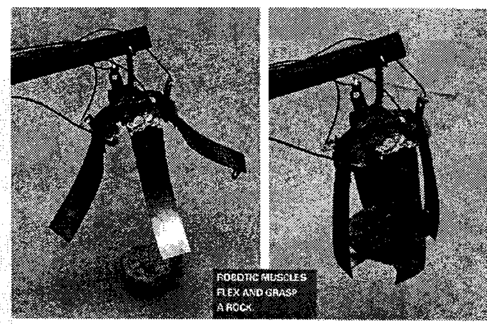
A bending EAP is being developed as a dust wiper for application considerations in the MUSES-CN mission



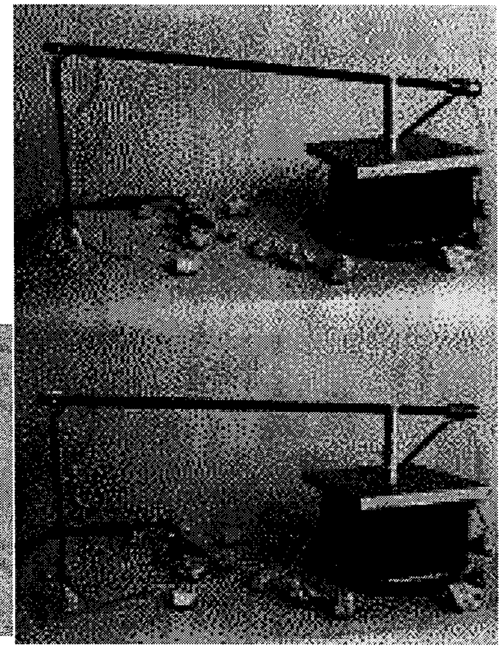
Miniature robotic arm

A stretching EAP is used to lower a robotic arm, while bending EAP fingers operate as a gripper. The technology is being developed to enable miniature sample handling robotics.





Discover Magazine, Aug. 98, p.33



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Longitudinal EAP Actuators

Electro-Statically Stricted Polymer (ESSP)

- Polymers with low elastic stiffness and high dielectric constant can be used to induce large actuation strain by subjecting them to an electrostatic field.
- Coulomb forces between electrodes can squeeze or stretch a sandwiched polymer material.
- Longitudinal electrostatic actuator can be made of a dielectric elastomer film (silicone) coated with carbon powder electrodes.
  - The force (stress) that is exerted on such a film with compliant electrodes is:

$$P = \varepsilon\varepsilon_0 E^2 = \varepsilon\varepsilon_0 (V / t)^2 \qquad (1)$$

Where: P is the normal stress, ε_0 is the permittivity of vacuum and ε is the relative permittivity (dielectric constant) of the material, E is the electric field across the thickness of the film, V is the voltage applied across the film and t is the thickness of the film. The Poisson's ratio is assumed as 0.5.

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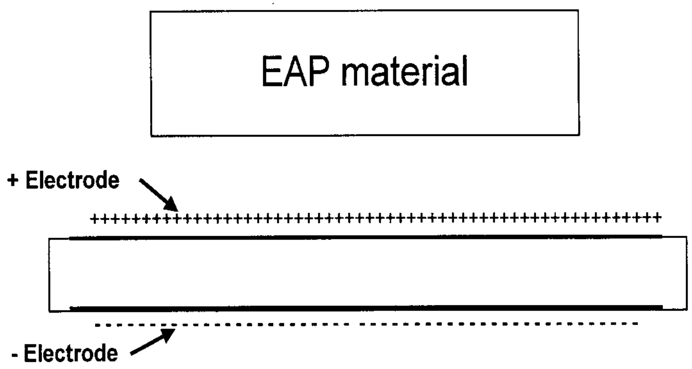
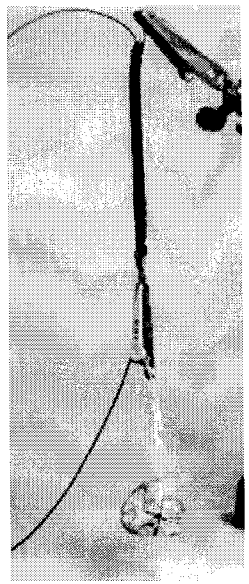
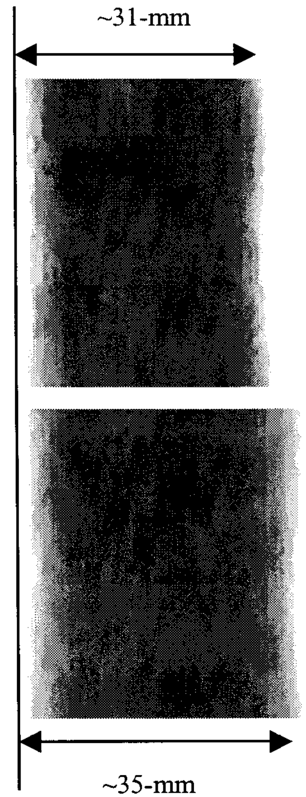
Longitudinal eap actuator

Electro-Statically Stricted Polymer (ESSP)

Under electro-activation, a polymer film with electrodes on both surfaces expands laterally.







EAP film subjected to 25 V/μm induced over12% extension

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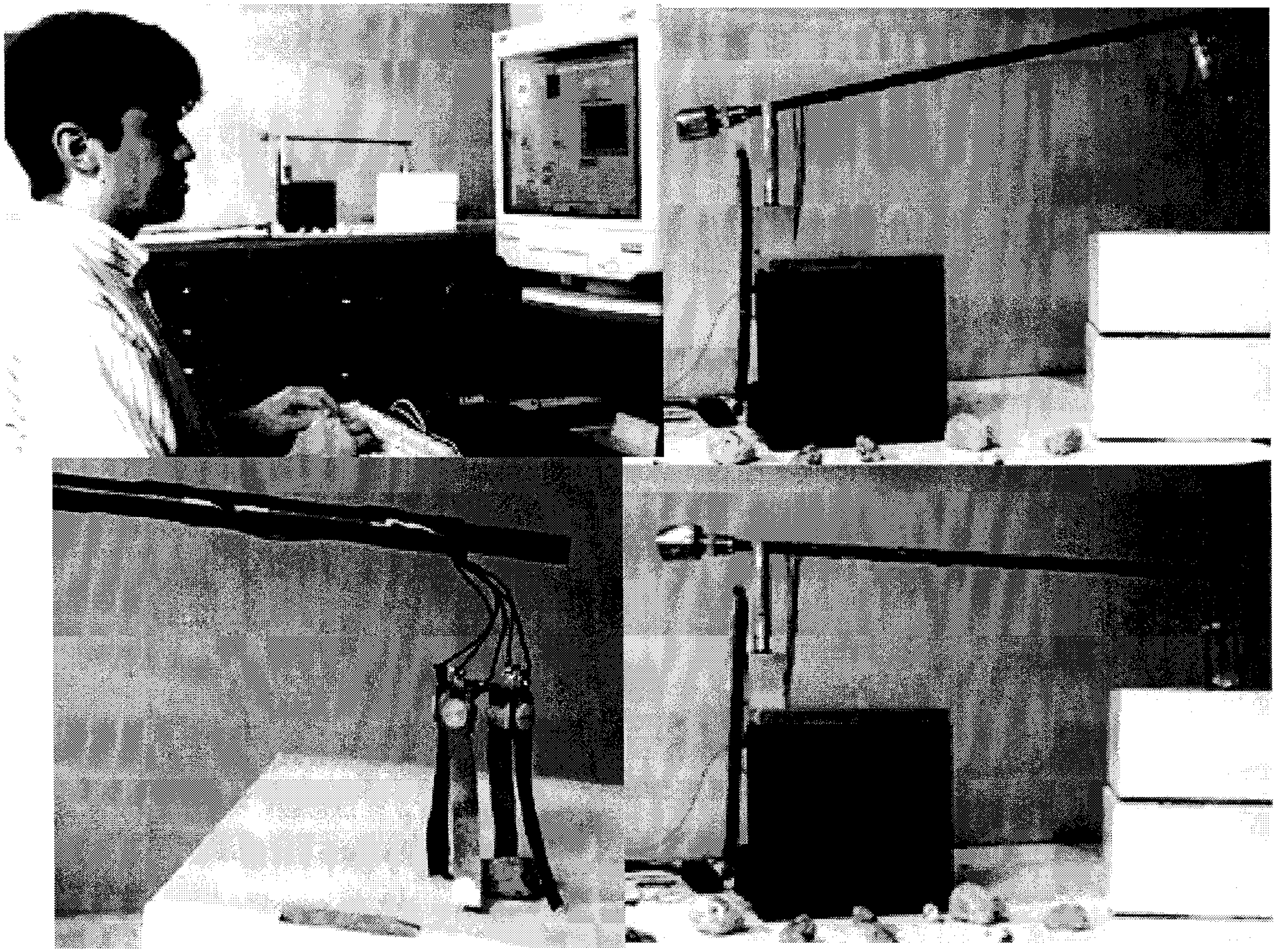
Robotic arm

A computer controlled arm with longitudinal EAP actuator serving as the lifter and bending EAP fingers as the gripper



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Bending EAP actuator/sensor

Capabilities

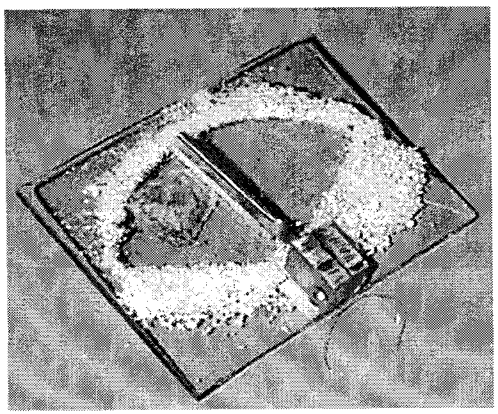
- IPMC induces large bending actuation strain
- It also induce the reverse phenomena, i.e., sensing bending strain
- Effective at low temperatures (-100°C) and vacuum (1-torr)
- Unique electrical resistance that grows with the decrease in temperature
- Capacitive behavior that is employed for power storage

Limitations

- Requires coating to prevent loss of the ionic content when operating in air
- Coating process involves wrinkling, blistering, off-axis bending and non-linear deformation
- Transverse deformation constrains the response
- Low actuation force
- Slow response to turn-off, retraction under DC-voltage and degrades by electrolysis at >2V
- Complex equivalent circuit characteristics

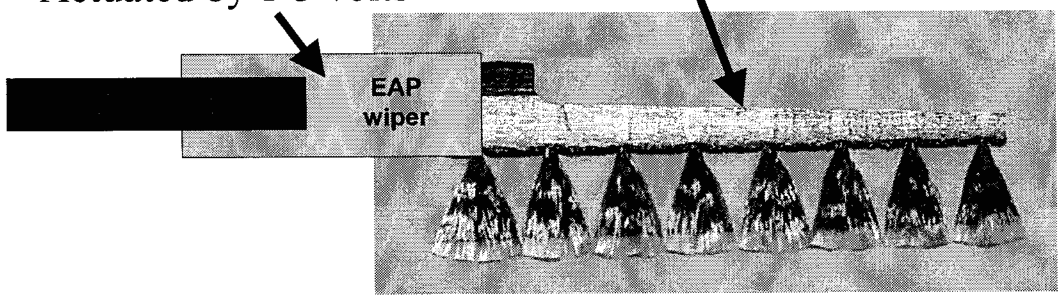
EAP actuated dust wiper

- Flight-like EAP dust wiper is being prepared at JPL using specifications of the MUSES-CN mission
- LaRC developed a unique protective coating
- ESLI developed effective wiper blades
- Osaka National Research Institute, Japan, is providing effective bending EAP
- Kobe University, Japan, is providing electromechanical modeling assistance
- VT is developing a self-assembled mono-layering technique for improved electroding

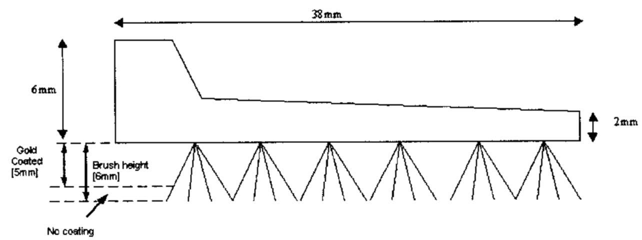


Biased with 1-2KV for dust repulsion

Actuated by 1-3 volts



Graphite/Epoxy wiper blade* with fiberglass brush coated with gold



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* Made by Energy Science Laboratories, Inc., San Diego, California

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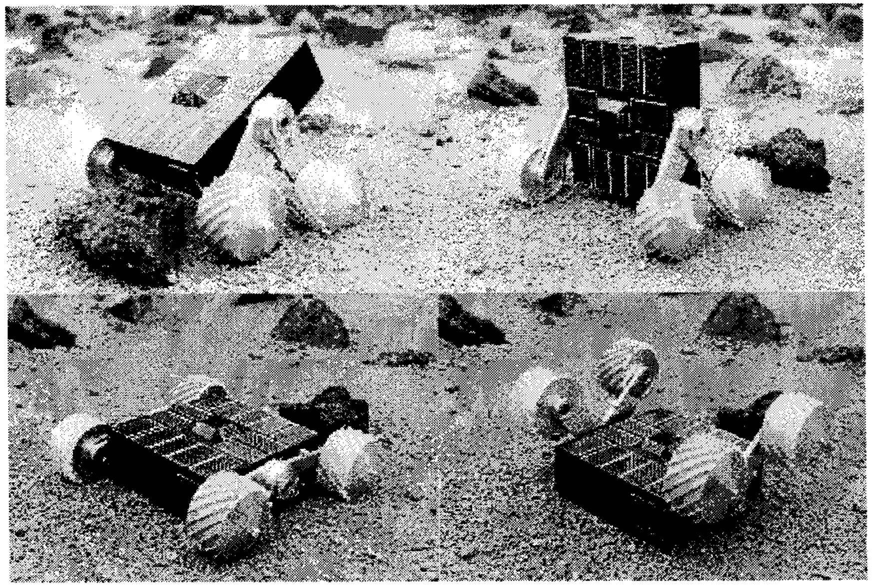
Planetary technical challenges

NanoRover



- Mars exploration requires removal of dust as small as 3.2μm diameter.

- Operation on an asteroid (MUSES-CN mission) requires addressing the effect of ionic radiation, UV and a large temperature range.
  - Overall the temperature range is: -155°C to +125°C and the desired operating range is -125°C to + 60°C

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Challenges and solutions to the application of IPMC as bending actuators

Challenge	Solution
Fluorinate base - difficult to bond	Pre-etching (LaRC)
Sensitive to dehydration (~5-min)	Etching and coating (NASA-LaRC)
Electroding points cause leakage	Effective compact electroding method was developed
Off-axis bending actuation	Use of load (e.g., wiper) to constrain the free end
Most bending occurs near the poles	Improve the metal layer uniformity
Electrolysis occurs at >1.03-V in Na+/Pt	• Minimize voltage • Use IPMC with gold electrodes and cations based on – Li^+ – Perfluorocarboxylate with tetra-n-butylammonium (ONRI)
• Survive -155°C to +125°C • Operate at -125°C to + 60°C	IPMC was demonstrated to operate at -140°C
Need to remove a spectrum of dust sizes in the range of >3μm	• Use effective wiper-blade design (ESLI, San Diego, CA) • Apply high bias voltage to repel the dust
Reverse bending under DC voltage	Limit application to dynamic/controlled operations
Developed coating is permeable	• Alternative polymeric coating • Metallic Self-Assembled Monolayer overcoat
Residual deformation	Still a challenge
No established quality assurance	• Use short beam/film • Efforts are underway to tackle the critical issues

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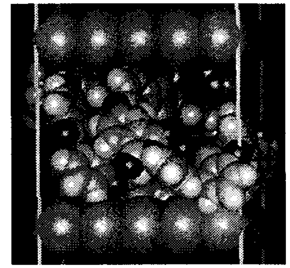
FEM Computational chemistry of EAP



- The improvement of the induced force capability of EAP is critical to making these materials the actuators of choice.
- Recent work at the NASA LaRC's Computational Materials Program used accurate quantum chemistry calculations to determine force fields for a range of polymers including polyimides.
- The calculated force field was experimentally verified (through thermo-physical and ultrasonic measurements).
  - The method was used to predict response to electric fields, mechanical stresses, and temperature.
- Planes of large spheres represent the metal electrodes, and are used to simulate the poling field. The properties from atomistic simulations are fed into large-scale finite-element models.
- So far, successful models at the atomistic, micro-mechanical, and continuum levels have been developed.

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Significant future applications

Mechanisms & Robotics

Muscle actuators that are resilient and damage tolerant will enable:

- Walking, crawling, swimming and/or flying miniature robots
- Insect-like robotic colonies that emulate ants.

Miniaturization

MEMS using EAP actuators and sensors.

Planetary applications

Recent JPL results, showing that bending-EAP are operating at low-temperatures and vacuum, have a great promise for space applications such as:

- EAP surface wiper for dust removal from optical/IR windows
- Miniature robotic arm for sample manipulation
- Under consideration: Support active/controllable inflatable structures

Transition to broad range of applications

Beneficiaries include: medicine, consumer products and military.

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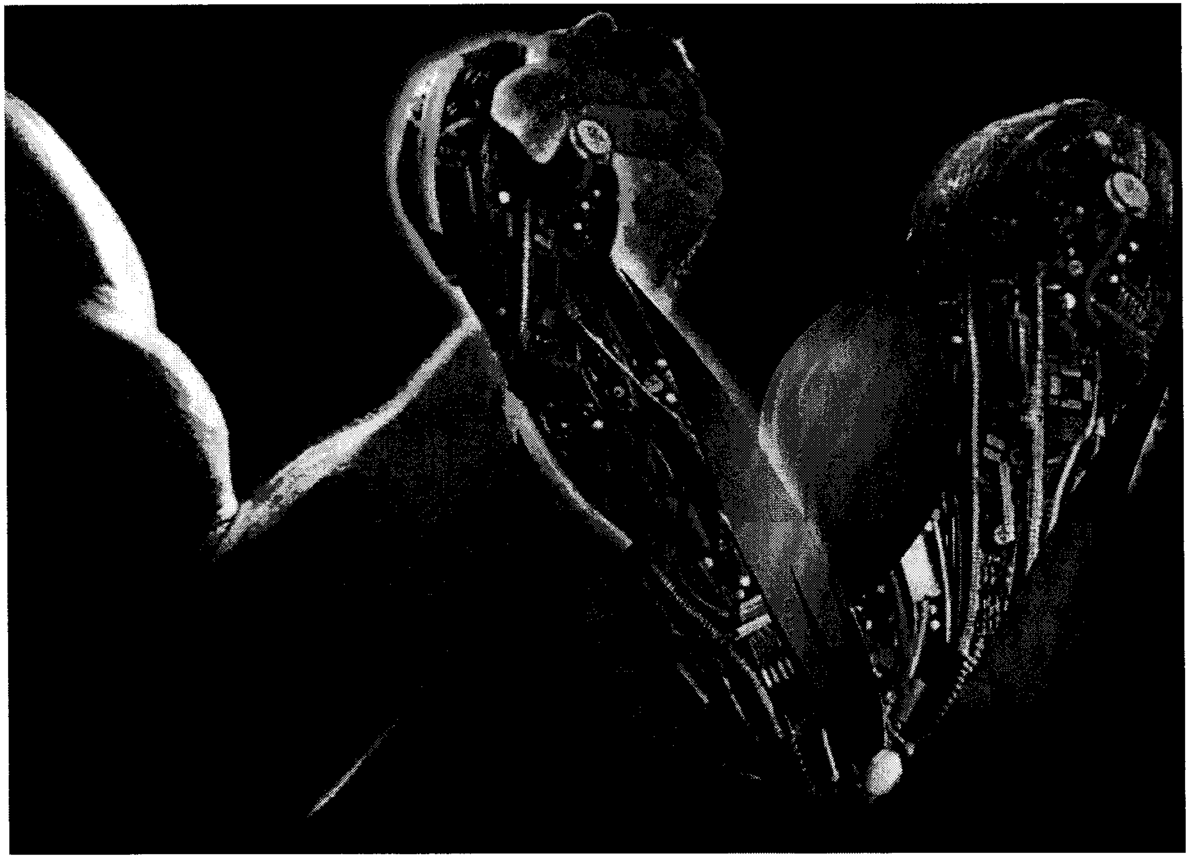
Summary

- Electroactive polymers (EAP) are emerging with capabilities that mimic biological muscles.
  - Inducing large displacements and can be made miniature, low mass, inexpensive, and consume low power.

- The technology enables unique actuation for various mechanisms, robotics and locomotion capabilities.

- The infrastructure of the field needs to be enhance and international collaboration among the developers and users is expected to lead to great improvement in the coming years.
  - Issues associated with their low force actuation capability and non-linear behavior requires attention.
  - Effective sensors are needed to track the large displacement as well as provide position information.
  - The resilience of the material and flexibility of the material poses control problems

The grand challenge for EAP as ARTIFICIAL MUSCLES



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